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Overview of Appalachian Basin High-Angle and Horizontal Air and Mud Drilling

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ABSTRACT

The United States Department of Energy's Morgantown Energy Technology Center has been investigating the potential of using high angle and horizontal drilling technology to improve gas production from low permeability reservoirs for more than 20 years. A chronology of 45 high angle and horizontal wells have been identified to show the date, type well, type build curve, location, formation and the type of application. The historical well drilling events that have taken place since the first well are discussed to evaluate the progress in developing the technology. Detailed discussion about how the drilling technology developed in the Appalachian Basin for directional drilling and completion was provided. A discussion of the types of applications for high and horizontal drilling in the Appalachian Basin were identified. A summary of four jointly funded DOE/Industry horizontal wells were discussed to illustrate how the air horizontal drilling technology developed and learning curves for drilling cost and feet per day were provided to illustrate the improvement in the technology and equipment reliability.

References and figures at end of paper.

INTRODUCTION

High angle and horizontal drilling in the Appalachian Basin originated in the early 1970's through Federal Government involvement with the development of unconventional gas resources such as Devonian shale and methane from coalbeds. Those early projects involved the utilization of high angle and horizontal drilling methods to improve wellbore contact with underground natural fracture systems for improved recovery of natural gas and the use of horizontal wells to efficiently burn coal in situ to create low quality gas using underground coal gasification methods. The earliest Appalachian Basin horizontal well consisted of a 3-inch pilot hole started at 20° inclination at the surface and intercepted the Pittsburgh coalbed at a vertical depth of 776 feet. To develop inclination, 1-3/4-inch mud motors were used, and BQ drill rod and stinger assemblies were used to permit overreaming of the pilot hole, such that 4 1/2-inch casing could be installed to protect the formation from caving and to permit the installation of pumping equipment for de-watering the coalbed for methane production. Improved confidence in being able to build angle with more rigid drilling tools de-emphasized the need for pilot holes followed by over-reaming and introduced the use of larger diameter motors to drill conventional hole sizes.

The relatively slow growth of the Appalachian Basin directional drilling industry has been caused by a number of factors: (1) relatively low permeability of oil and gas reservoirs compared to other Basins, (2) cheap vertical well drilling ($25 - 45/foot) associated with the efficient use of air drilling technology, (3) inadequate well siting methodology, and (4) lack of suitable and affordable air directional drilling equipment. With the recent developments of positive displacement motors designed to improve the rate of penetration and improved surveying methods while air drilling horizontal wells, the drilling cost is being reduced and operators should become more interested in using high angle and horizontal wells.

HISTORICAL WELL DRILLING

Since 1969, the U. S. Department of Energy's Morgantown Energy Technology Center (DOE/METC) has been investigating the concept of multiple hydraulic fracturing of a high angle well perpendicular to a directionally controlled, naturally fractured, reservoir to improve production performance and ultimate, producible reserves[1]. In 1972, the first Appalachian Basin high angle directional well was drilled in Devonian Shale in Mingo County, West Virginia[2] as shown in Figure 1. This 43° directional well was a jointly funded project between Columbia Gas and DOE/METC (formerly U. S. Department of Interior). In 1973, the first horizontal well in the Appalachian Basin was drilled by the Pittsburgh Bureau of Mines in Greene County, Pennsylvania, near the town of Jollytown, Pennsylvania[3]. The 414-foot horizontal well was drilled for coalbed methane degasification ahead of active mining operations. These two wells marked the beginning of the Appalachian Basin directional and horizontal drilling industry for improving production from naturally fractured reservoirs. In the fall of 1975, the Pittsburgh Bureau of Mines drilled six pilot horizontal holes totaling 2,205 feet from a single well directionally drilled from surface to intersect the coal. The well was horizontal at a true vertical depth of 999 feet and measured a depth of 1,213 feet[4]. During 1976, DOE/METC drilled a 507-foot horizontal well in the Pittsburgh coal seam near Priceton, West Virginia, in support of testing the "long-wall generator concept" for underground coal gasification.

Beyond the early wells, the use of high angle and horizontal drilling for improving production was slow to develop. In 1978, the DOE and Consolidated Natural Gas Supply Corporation jointly drilled a 52° high angle directional well targeted for Devonian Shale in the Cottageville Field in Jackson County, West Virginia[5], as shown in Figure 2. Beginning in the fall of

1978, the Pittsburgh Bureau of Mines conducted a multi-drain horizontal well project at the Emerald Mine near Waynesburg, Pennsylvania. Three primary horizontal methane drainage holes totaling 7,967 feet were completed in the Pittsburgh coalbed from a single directional surface hole. Overall, a total of five multi-drain horizontal holes from one well were extended a total of 10,882 feet with the longest single drainage hole attaining 3,207 feet (the longest horizontal well in the Appalachian Basin)[6].

Over the next several years, the petroleum industry utilized high angle and horizontal wells for other applications such as remote access and solution mining. In 1986, DOE, BDM Corporation, and Eneger Corporation drilled a 2,000 foot horizontal well in Devonian Shale in Wayne County, West Virginia[7], as shown in Figure 3. Total horizontal displacement was 3,186 feet from vertical at a measured depth of 6,020 feet. During 1988 an Industry consortium of companies drilled a 1,530-foot horizontal well in the Medina Sand in Crawford County, Pennsylvania. Following the horizontal well in the Medina Sandstone, several Industry operators have attempted to utilize high angle drilling for improved production and remote access applications in the Devonian Shale, Berea, Clinton, and Big Lime Formations. In 1989, a DOE, Sterling, GRI, Columbia, and Pennzoil jointly funded 71° slant well was drilled in Devonian Shale as shown in Figure 4. The well had over 1,600 feet of exposure to producing interval.

During 1989, DOE, BDM, and Cabot Corporation jointly drilled a 1,789-foot horizontal well in Putman County, West Virginia, targeted to the Devonian Shale as shown in Figure 5. Total horizontal displacement was 2,618 feet from vertical at a measured depth of 6,399 feet. In 1990, two jointly sponsored Devonian Shale horizontal wells were drilled. One, a DOE and Columbia Gas 1,985-foot horizontal well in Martin County, Kentucky, which was drilled to a measured depth of 6,263 feet as shown in Figure 6. The other, a DOE, BDM, CNG, and Prime Energy 1,617-foot horizontal well, which was drilled in Calhoun County, West Virginia, to a measured depth of 5,013 feet as shown in Figure 7.

In 1991, the utilization of slant hole (30-35°) directional drilling has been economically used to develop Clinton-Medina Sandstone production in Ohio[8]. The application involves directional drilling under Berlin Lake in Ohio.

DRILLING TECHNOLOGY DEVELOPMENT

In 1972, positive displacement mud motors using an unsealed bearing 1:2 Moineau rotor/stator high speed, low torque, configuration were used with an air/mist circulating system to change the inclination and direction of the wellbore while drilling. A wireline conveyed magnetic single shot survey instrument was used to directionally survey. After the desired inclination was achieved, various bottom hole assemblies were tried to maintain the wellbore's trajectory.

Until 1976, high-speed, low-torque mud motors were the only downhole motors available on the market. When run with air/mist they exhibited surprisingly high RPM's, which resulted in significant bit and motor failures.

Single shot survey technology requires considerable rig time to orient downhole motors. Without continous orientation of the downhole motor, erratic build sections occur.

In 1978 the first known application of single conductor wireline steering tools with air/mist directional drilling was attempted. The durability of the first generation of steering tools became immediately apparent with a short mean time between failure. High-speed, low-torque motors were still being used with a small increase in motor life resulting from improved mist formulas. Short bit life, over heated rotor/stators, broken u-joints and bearing failures were very common problems associated with the motors high RPM's.

By 1982, multilobe positive-displacement mud motors were becoming more available to the drilling industry. The multilobe allowed high torque and relatively low bit speeds in comparison to past motors. This allowed more weight to be applied to the bit and provided a significant increase in the rate of penetration. In addition, stator and bearing failure rates decreased. In late 1983 the use of multilobe positive-displacement mud motors with sealed bearings for air/mist directional drilling began. By 1989 these sealed bearing motors would operate on air/mist over 50 hours under proper operating conditions[9].

Typical drilling in the Appalachian Basin with air/mist used 2,000-3,000 Standard Cubic Feet Per Minute (SCFM) in a stand pipe pressure range between 100 and 300 psi. High pressure air (300 psi - 800 psi) was used to improve hole cleaning and extra motor cooling[10] and improve the mean time between failure of the wireline steering tool. Instantaneous penetration rate did not increase significantly, but overall drilling efficiency improved because of a significant improvement in the performance of the steering tool and downhole motors.

Horizontal and high angle drilling with mud in the Appalachian Basin followed the chronology of the rest of the non-air drilling industry. Because of the relatively slow rate of penetration with this type of drilling, it was confined to areas of the Basin where it was economical. However, there were instances when both air and mud circulating systems were used to improve the accuracy of the positioning of the bore hole. In these cases mud was preferred over air to permit the use of MWD in building the curve to horizontal an air/mist was used to drill the horizontal portion of the well.

During 1986, adjustable bent housin motors became available in the Appalachian Basin. In comparison t the straight motors with bent subs, that had been used previously, thes motors allowed more control of the build up rates. In addition, improvement of the rotor/stator configuration of the motors allowed more weight to be applied to the bit. The low stall weight for motors still remained a problem to achieving high penetration rates.

Also, in 1986, an "electromagnetic measurement while drilling system" was introduced to steer the downhol motors. The initial runs resulted in a very low mean time between failures, which resulted in further development of the tool.

Wireline steering tool technology had been progressing. More rugged sensor packages became available at the same time instrument stabilization assemblies were being developed. All of the above permitted longer motor runs using steering tools. In 1988, the use o another "measurement-while-drilling system" was attempted. It employed a "modified for air" drilling mud pulse telemetry system and did not perform well enough to merit furthe development. But the concept of measurement while drilling was stil required, so the DOE and Industry stepped up research and development on using wireless measurement-while-drilling systems for air drilling[11].

In late 1989 the first downhole motor for air directional drilling was field tested. Initial tests showed dramatically improved rates of penetration using typical air packages in the Basin[14]. The motor was designed with an adjustable bent housing between the motor and the sealed bearing assembly.

The improved stabilization and resulting improvement in reliability of wireline steering tools have permitted longer motor runs and increased drilling efficincy in the build curve sections of the horizontal wells. However, surveying the horizontal section in the absence of a mmeasurement-while-drilling (MWD) system can be most economically accomplished by the use of short trips for running non-magnetic releasing single shots and wireline retrievable over-shots to obtain single shot survey data. This method still consumes too much time for surveying. Methods to permit the rotation and orientation of wireline steering tools are being investigated as an alternative to the full-blown development of a wireless MWD system. The reliability and utility of such a system is yet to be field proven as an intermediate step toward air MWD.

Development of a wireless measurement-while-drilling system for air continues with system hardening and data transmission reliability at the focus.

In summary, the performance of air downhole motors is satisfying industry needs while an adequate surveying system is still under development. When that system is operating satisfactorily, then the air drilling of high angle and horizontal wells will match or exceed the performance of mud systems.

APPLICATIONS

Forty-five high angle and horizontal wells have been identified in the Appalachian Basin. Their chronology, type, build curve, location, formation, and application type have been listed in Tables 1, 2, and 3. Table 4 shows, in ranked order, the type of applications for high-angle horizontal drilling in the Appalachian Basin.

This type of drilling has been developing as a response to industry's demand for new production methods of previously neglected pay intervals. The use of high angle and horizontal wells has been predominantly focused on the following applications:

1. Naturally fractured (formations where drilling perpendicular to the natural fractures produces oil and gas in commercial quantities).

2. Solution mining (formations where the dissolving of large volumes of salts and anhydrites into highly saturated solutions is produced in commercial quantities).

3. Remote access (producing formations beneath inaccessible locations that can not be more economically produced by any other method).

4. Methane drainage (shallow, low pressure, high volume reservoirs in coal seams that can not be more economically produced).

5. Underground coal gasification (developments of a new energy source by in-situ burning of coal).

DOE/INDUSTRY DEVONIAN SHALE HORIZONTAL TEST WELLS

A total of four, long air-drilled, horizontal test wells have been completed since 1986, as shown in Table 5. Each test well will be summarized below:

Test Well Summaries:

The Ret #1 well is the first and longest air-drilled horizontal well in the Appalachian Basin. This test well was drilled in the Cabwaylingo State Forest in Wayne County, West Virginia. The objective of the well was to evaluate the recovery efficiency of using multiple hydraulic fracturing in a long horizontal well to recover gas from tight naturally fractured Devonian Shale.

The drilling and completion activities consisted of installation of 660 feet of 16-inch casing followed by 2,024 feet of 11 3/4-inch casing. Kickoff point was 2,113 feet where 7 3/4-inch multi-lobe straight, positive-displacement mud motors and bent subs drilled a 10 5/8-inch hole to 74° of inclination where 3,803 feet of 8 5/8-inch casing was installed. Hole cleaning mandated the casing setting depth. 6 3/4 inch adjustable multi-lobe positive-displacement mud motors and wireline steering tools were used to build the well to horizontal where 73 feet of oriented horizontal core was obtained. Following coring, rotary drilling assemblies and single shot surveying were used to drill the 2,000-foot horizontal section to 6,020 feet MD. A total of 11 motors were run with a mean time between failures of 10 hours. Several wire line probes were also used to build the curve. An experimental electromagnetic MWD was tested in the build curve section. Drill pipe conveyed well logs and video camera were run, followed by installation of 6,011 feet of 4 1/2-inch casing containing 8 external casing packers, 1 cement-filled packer, and 14 port collars. A total of 8 zones were isolated for extensive stimulation research[13].

The Hardy HW#1 well was the second DOE/Industry horizontal well located in Putnam County, West Virginia. The drilling and completion activities consisted of installation of 658 feet of 13 3/4-inch casing followed by 2,654 feet of 9 5/8-inch casing. Kickoff point was 3,253 feet, where two types of 6 3/4 inch adjustable multi-lobe positive displacement motors were used to build the well to horizontal at 4,610 feet of measured depth. A total of seven wireline steering tool failures occured during the drilling of the build curve. An experimental electromagnetic MWD tool was tested in the build curve section. The 7 7/8-inch horizontal section was drilled with rotary assemblies from 4,610 to 6,399 feet MD. At 5,670 feet MD, the drill pipe would no longer fall during connections without rotating the pipe. Surveying of the horizontal section was achieved using a monel sensor releasing overshot, which was used to run single shot surveys by making short trips of the drill pipe out to a free fall inclination. Drill pipe-conveyed open hole well logs were run to 6,360 feet MD. These were followed by installation of 6,150 feet of 4 1/2-inch casing, which contained five external casing packers and four port collars. A total of four zones were isolated for stimulation.

The PDC #21747 well was the third DOE/Industry long horizontal well drilled in Martin County, Kentucky. Drilling and completion activities consist of installation of 791 feet of 13 3/8-inch casing followed by 2,548 feet of 9 5/8 inch casing. An 8 3/4-inch hole was drilled to 3,055 feet at kickoff point. To build the curve section to horizontal at 4,238 feet of measured depth, a 6 3/4-inch low speed, high torque, multi-lobe, positive-displacement motors and wire line steering tools were used. An experimental, electromagnetic MWD tool was run to evaluate tool reliability. The horizontal section was drilled with rotary assemblies to a measured depth of 6,263 feet using an 8 3/4-inch bit. Drill pipe conveyed logs were run to 6,088 feet of measured depth, 175 feet short of drillers depth of 6,263 feet. Cement inflatable packers (five) containing 6,013 feet of 5 1/2-inch casing was run, four port collars, and a cementing tool. The completion was setup to have a slotted liner in the zone near total depth. A total of six zones were available for stimulation with the inflatable packers set using Potassium Cloride water and four zones were used as open hole sections and two zones were cemented. A portion of the build curve was also productive providing a total of 3,203 feet of stimulation interval.

The Hunter Bennett #3997 well was the fourth DOE/Industry horizontal well drilled in Calhoun County, West Virginia. The drilling and completion consists of installation of 258 feet of 13 3/8-inch casing followed by 2,096 feet of 9 5/8-inch casing. Building the curve to horizontal at 3,280 feet MD, was accomplished by using 6 3/4-inch low speed, high torque, multi-lobe, positive displacement motors on 8 3/4- and 8 1/2-inch bits . Two motors were used to build the entire curve. Wireline steering tools were used to survey the build section. Three steering tool failures occured. The horizontal section was drilled using rotary tools to a depth of 5,013 feet and surveyed using single shot technology. Drill pipe-conveyed well logs were run and 4,755 feet of 5 1/2-inch casing was run containing six external casing packers and nine port collars. A total of five zones were isolated by the fluid inflated casing packers. The well currently has not been stimulated.

Evaluation of drilling statistics shown in Table 6 demonstrate an overall reduction from 58 to 21 days for similar well configurations. Increased motor life and improved steering tools have reduced the drilling cost per foot, and the footage drilled per day has increased, as shown in Table 7. As the number of long horizontal wells drilled by operators in an area increases, a learning curve develops which improves the economics. A Devonian shale learning curve has been developed from the DOE/Industry test wells as shown in Figure 8. Up to a 33%

reduction in drilling cost per foot and over a 100% increase in feet per day has resulted from these DOE/Industry test wells.

PRODUCTION RESPONSE TO HORIZONTAL DRILLING

Thousands of vertical wells have been drilled in Devonian Shale with mixed results relative to productivity improvement. Site selection remains critical to economical vertical well. Reserves rang from 100 - 290 million cubic feet (MMCF). Based on the 4 DOE/Industry long horizontal wells, horizontal drilling has the potential to improve the initial production rates from 3 to 10 fold. The objective of verifying improved gas production by these test wells has been achieved based on initial production. From an economic point of view, only one of the four test wells has been proclaimed by the operator as a "commercial well" with an initial open flow rate of 3.1 million cubic feet per day (mmcfd) compared to the average vertical well having less than .3 mmcfd[14]. Production results, compared to vertical wells, are shown in Figures 9 and 10 for two of the long horizontal wells. Results indicate a 3 fold increase in production.

Personal communication with operators, relative to production results from mud and air-drilled directional wells, indicates that mud-drilled gas wells in the Appalachian Basin do not produce as well as air-drilled gas wells. Production differences may be attributed to formation damage. Rock pore pressures in the Appalachian Basin are low at .2 to .5 psi/ft. In situ stress values range from .4 to 1.1 psi/ft. In many areas, drilling with mud causes overbalanced drilling and a reduced rate of penetration. Drilling fluids typically invade the high permeability zones (natural fractures) causing irrepairable damage to the fracture system. Insufficient reservoir pressure is available to remove drilling fluid.

CONCLUSIONS

1. Significant technology improvements associated with air motor performance offers hope for reduced well costs.

2. Formation damage associated with non-air drilled high angl wells may be contributing to the lack of production success in low permeability gas reservoirs in the Appalachian Basin.

3. Steering tool reliability need to be improved such that the total drilling system efficiency can be increased.

4. Horizontal drilling is in an early stage of development in the Appalachian Basin and additional economically viable wells will have to be demonstrated prior to full acceptance by basin operators.

5. A reliable air MWD system need to be perfected to improve horizontal drilling efficiency

NOMENCLATURE

H	-	Horizontal Well
HA	-	High Angle (> 40°)
SR	-	Short Radius
MR	-	Medium Radius
LR	-	Long Radius
NF	-	Naturally Fractured
LP	-	Low Permeability
SM	-	Solution Mining
RA	-	Remote Access
UCG	-	Underground Coal Gasification
MD	-	Methane Drainage

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Table 1
Chronology of High Angle/Horizontal Wells in Appalachian Basin

Date	Type Well	# Wells	County/State	Formation	Reason
1972	HA - 43°	1	Mingo/WV	Dev. Shale	NF
*1973	H - LR	1	Greene/PA	Coal	MD
*1975	H - LR	1	Greene/PA	Coal	MD
*1976	H - LR	1	Wetzel/WV	Coal	UCG
1978	HA - 52°	1	Jackson/WV	Dev. Shale	NF
*1978	H - SR	1	Jackson/WV	Dev. Shale	NF
*1978	H - SR	1	Boone/WV	Dev. Shale	NF
1979	H - MR	1	Greene/PA	Coal	MD
1983	HA - 49°	1	Tucker/WV	Oriskany	RA
1986	H - LR	1	Wayne/WV	Dev. Shale	NF

*Mud Drilled

Table 2
Chronology of High Angle/Horizontal Wells in Appalachian Basin

Date	Type Well	# Wells	County/State	Formation	Reason
*1986	H - SR	1	Summit/OH	Salina Salt	SM
1987	HA - 40°	6	Harlan/KY	Big Lime	RA/LP
*1987	H - SR	3	Summit/OH	Salina Salt	SM
1987	H - MR	1	Buchanon/VA	Coal	MD
1988	HA - 60°	7	Logan/WV	Dev. Int.	NF/RA
*1988	H - SR	1	Summit/OH	Salina Salt	SM
1988	HA - 68°	1	Martin/KY	Dev. Shale	NF
1988	H - MR	1	Crawford/PA	Medina	LP
*1989	HA - 70°	1	Mahoning/OH	Clinton	LP/RA
1989	HA - 72°	1	Roane/WV	Dev. Shale	NF
*1989	HA - 50°	1	Trumbull/OH	Clinton	LP/RA

*Mud Drilled

Table 3
Chronology of High Angle/Horizontal Wells in Appalachian Basin

Date	Type Well	# Wells	County/State	Formation	Reason
1989	HA - 53°	1	Wyoming/WV	Dev. Int.	NF/LP
1989	H - MR	1	Putnam/WV	Dev. Shale	NF
1990	HA - 72°	1	Washington/OH	Dev. Int.	NF
1990	H - MR	1	Calhoun/WV	Dev. Shale	NF
*1990	H - MR	1	Summit/OH	Salina Salt	SM
*1990	H - MR	1	Harlan/KY	Big Lime	SM
1990	H - MR	1	Martin/WV	Dev. Shale	NF
*1991	H - MR	1	Summit/OH	Salina Salt	SM
*1991	H - MR	1	Wyoming/NY	Salina Salt	SM
*1991	H - MR	1	Marshall/WV	Salina Salt	SM
1991	HA - 70°	1	Lincoln/WV	Berea/ Dev. Shale	NF

*Mud Drilled

Table 4
Applications for High Angle and Horizontal Wells Appalachian Basin

- Naturally Fractured
- Solution Mining
- Remote Access
- Methane Drainage
- Low Permeability
- Underground Coal Gasification

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Table 5
DOE/Industry Horizontal Drilling Projects
(Devonian Shale/Appalachian Basin)

Well Name	Location	Participants	Flow Rate (This Well)	Flow Rate (Avg. Vert. We
Ret #1	Wayne Co., WV	DOE/BDM/ENEGER	65 MCFD	13 MCFD
Hardy HW #1	Putnam Co., WV	DOE/BDM/CABOT	125 MCFD	40
PDC #21747	Martin Co., KY	DOE/COLUMBIA	3100 MCFD (2)	270 (2)
Hunter Bennett #3997	Calhoun Co., WV	DOE/BDM/CNG/ PRIME ENERGY	80 MCFD (3)	83 MCFD

(1) – 1600' Slant Well at angle of 72 deg.
(2) – Final Open Flow
(3) – PreFrac Open Flow

Table 6
Comparative Horizontal Drilling Statistics

	Interval		No. Days
Ret #1			
Surface	0-2113'		18
Build	2113'-4020'		27
Horizontal	4020'-6020'		13
		Total Days	58
Hardy #1			
Surface	0-3253'		14
Build	3253'-4615'		8
Horizontal	4615'-6404'		9
		Total Days	58
Hunter Bennett #1			
Surface	0-2165'		5
Build	2165'-3280'		8
Horizontal	3280'-5013'		8
		Total Days	21

Table 7
Devonian Shale Horizontal Air Drilling Statistics
- 2000' Horizontal Wells -

Well	Location	Total Days	Total Measured Depth	Drilling Cost	$/ft	ft/day
Ret #1	Wayne Co., WV	58	6020	866K	144	104
Hardy #1	Putnam Co., WV	31	6404	587K	92	207
Hunter Bennett #1	Calhoun Co., WV	21	5013	549K	110	239

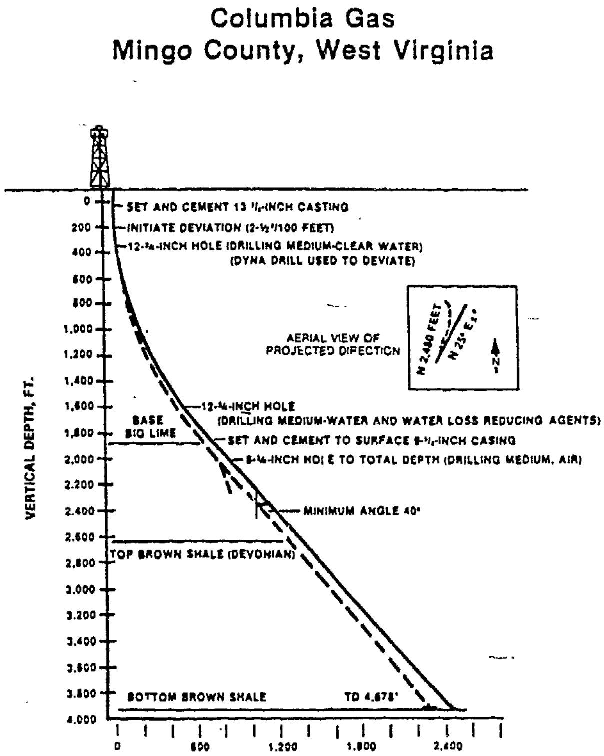

Fig. 1—First high-angle well in Appalachian Basin.

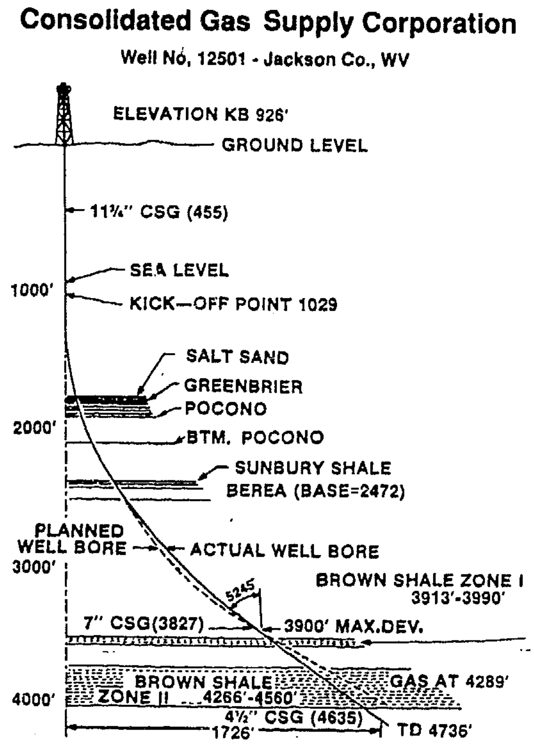

Fig. 2—52° high-angle well in Devonian shale.

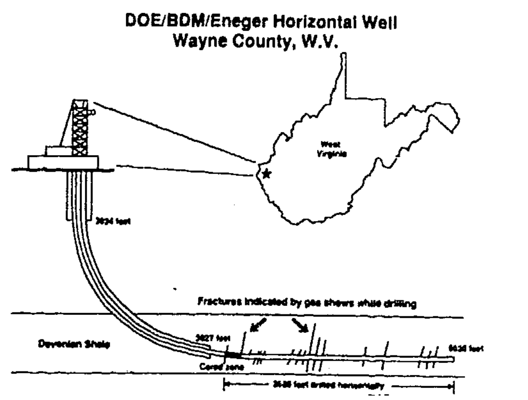

Fig. 3—First and longest air-drilled horizontal well in Appalachian Basin.

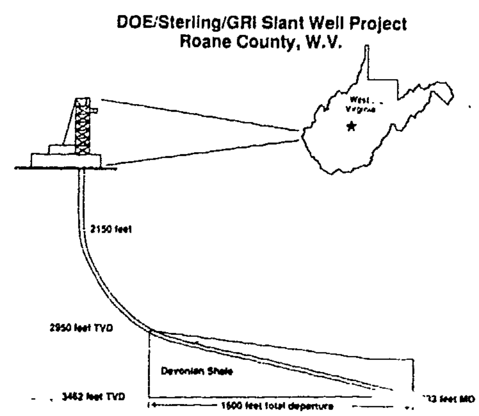

Fig. 4—71° high-angle well in Devonian shale.

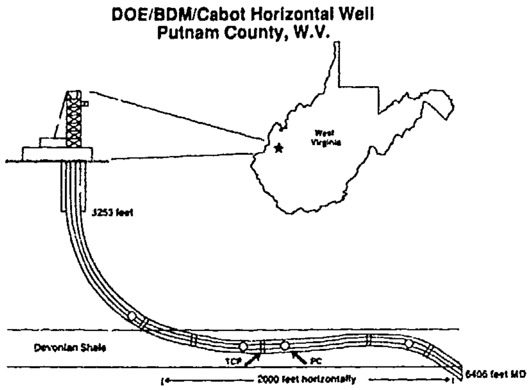

Fig. 5—Wellbore schematic for Cabot air-drilled horizontal well.

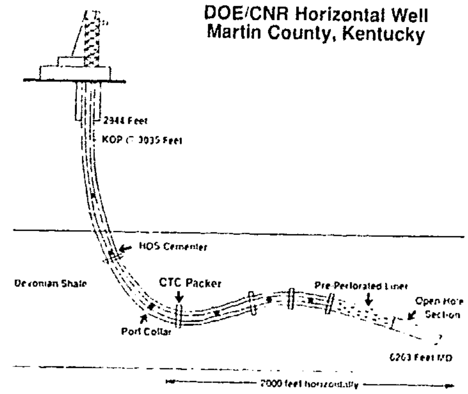

Fig. 6—Wellbore schematic for Columbia air-drilled horizontal well.

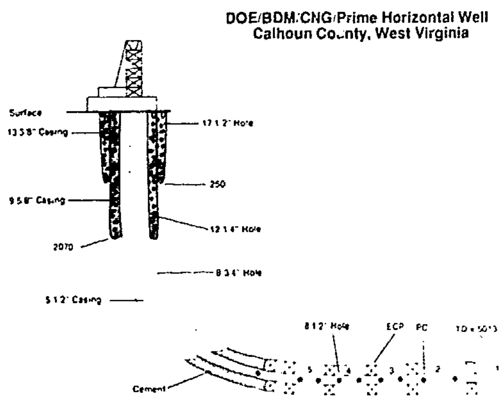

Fig. 7—Wellbore schematic for CNG air-drilled horizontal well.

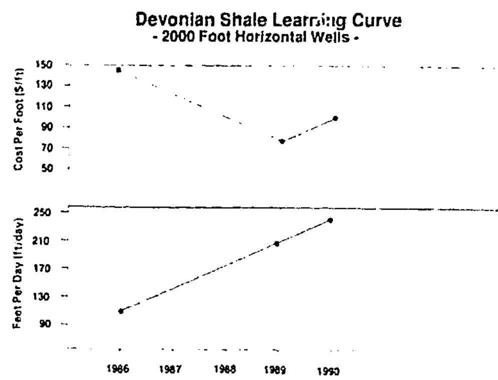

Fig. 8—Learning curve for 2,000-ft air-drilled horizontal wells.

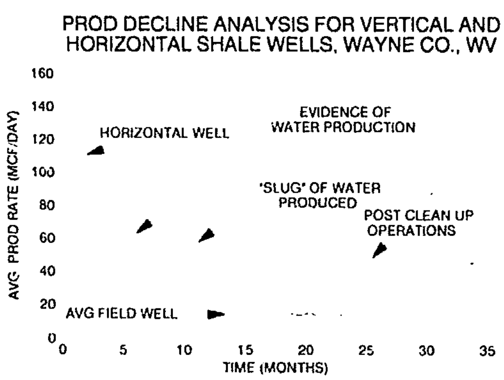

Fig. 9—Production decline for the Rat No. 1 well.

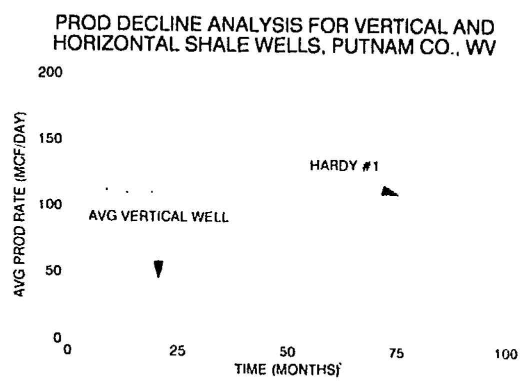

Fig. 10—Production decline for the Hardy HW No. 1 well.